

Present Epoch Plus - An X-ray survey for Cosmology

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This paper summarizes some cosmologically interesting measurements which are uniquely possible in the hard X-ray band and presents a mission concept capable of achieving them. The Present Epoch Plus mission will achieve a surface brightness sensitivity of better than 1% per square degree in the 2-10 keV band, and create a catalog of $\sim 10^6$ sources. About 160,000 extragalactic sources are expected to be detected in the 2-10 keV band, providing an all sky survey with nearly uniform selection effects 10 times deeper than existing or planned surveys. The PEP concept can be achieved within the size and budgetary constraints of a NASA Medium Explorer (MIDEX) mission.

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1. Introduction

Like the Cosmic Microwave Background (CMB), the Cosmic X-ray Background (CXB) above 2 keV is dominated by an apparently diffuse emission of distant origin. The CXB is due to the superposition of numerous unresolved point sources, and the bulk of the CXB is known to arise from redshifts $z \geq 1$ even though the details of the source populations remain unknown. The CXB provides an ideal observational tool for studying large scale structure in the universe at redshifts much greater than those accessible to catalogs of individual objects (which are always dominated by nearby objects) and at redshifts much less than the CMB. Using this tool requires an experiment capable of resolving and removing the foreground point sources of X-ray emission. This paper presents some problems that are uniquely addressed by a mission capable of producing both precise surface brightness measurements and deep X-ray catalogs, and sketches a mission concept that achieves these goals.

2. Problems Uniquely Addressed by X-ray Missions

Several groups have created plausible models for the origin of the CXB integrating over the X-ray luminosity functions of various sources, accounting for redshift and evolution (e.g. Comastri et al. 1995). The common feature of all models is that the bulk of the CXB arises between redshifts of 1 and 3. Using the CXB to study large scale structure does not depend on the details of the source populations, but only the assumption that X-ray light traces the underlying matter distribution. We highlight a few problems which CXB observations may be uniquely suited to address.

2.1. Velocity with respect to the Baryonic Universe

The largest anisotropy in the CMB, the dipole with amplitude ~ 0.001 of the mean CMB intensity (Smoot et al. 1992), is widely interpreted as the signature of peculiar motion, with respect to the CMB, due to gravitational acceleration from local anisotropies in the mass distribution. This interpretation is not controversial; however, it is central to much of cosmology, has not been verified by an independent measurement, is not the only explanation (Langlois and Piran 1996), and is apparently in conflict with a measurement of our velocity with respect to a reference frame defined by Abell clusters of galaxies (Lauer and Postman 1994). Confirmation of the peculiar motion interpretation would come from the measurement of a similar dipole with respect to distant (i.e. beyond the region producing gravitational acceleration) sources. Candidate distant sources are the CXB surface brightness

distribution and a population of $> 10^4$ X-ray sources all more distant than a few 100 Mpc. Either sample requires separation of the foreground emission which may be anisotropic due to luminosity associated with the mass responsible for the peculiar velocity. The HEAO-1 A2 survey has the statistical sensitivity to measure the expected dipole (Shafer 1983) but is unable to separate foreground and background emission (Jahoda 1993). Searches for dipole terms in catalogs of point objects (Maoz 1994, Rauch 1994, Scharf et al. 1995) have fallen an order of magnitude short of the number of objects required to detect this signal above the shot noise.

2.2. Power Spectrum on scales of 100 - 1000 Mpc and Intermediate Redshift

Models of structure formation in the universe are challenged to construct models that simultaneously describe the initial conditions observed by COBE with characteristic scales of > 1000 Mpc and $z \sim 1000$ and the present day universe observed by galaxy surveys such as IRAS and which cover scales of a few to a few tens of Mpc at the present epoch (i.e. $z \sim 0$) (Fischer et al. 1993). Even as the angular scales are pushed closer (MAP and Planck Surveyor will measure the CMB on sub degree scales while the Sloan Digital Sky Survey (SDSS) will provide dense samples of galaxies to distances at least ten times greater than IRAS) the extrapolation in z remains. The CXB, if measured on 1 square degree scales, probes $z \sim 1$ and scales of 100 to 1000 Mpc, helping bridge the gap and providing information at an epoch which can distinguish several theories of structure formation. An experiment which also identifies and removes the foreground sources provides a second chance to measure the power spectrum at recent epochs. A measurement made with X-ray selected sources is complementary to a similar measurement with optically (or otherwise) selected source as X-ray sources are relatively rare, and thus give better sensitivity at somewhat larger scales. In addition, the details of how X-ray sources trace the underlying matter distribution (often called the bias factor) may be quite different than for other populations, emphasizing the value of measurements in numerous bands.

2.3. Searches for a Cosmological Constant

In some critical density cosmologies, some CMB fluctuations arise as late $z \sim 1$. These fluctuations are due to a net Doppler shift experienced by microwave background photons which traverse expanding potential wells. This is known as the Rees-Sciama effect or the integrated Sachs-Wolfe effect, depending on whether the gravitational perturbation is in the linear or non linear regime (Bennett et al. 1993; Boughn et al. 1997). If X-ray light traces the matter distribution and therefore the gravitational potentials, one expects a correlation between X-ray surface brightness and CMB brightness. Correlations of the HEAO-1 A2 and COBE DMR maps fail to detect such a signal (Boughn et al. 1997) but the sensitivity is limited primarily by the size of the beam in both experiments which washes out small scale fluctuations. However, the MAP and Planck Surveyor experiments are being prepared to measure CMB fluctuations of scales < 1 square degree. An X-ray surface brightness map with similar angular resolution is needed extend this search.

2.4. X-ray catalogs

Uniformly selected source catalogs in different bands illuminate different aspects of our universe and discover rather different kinds of sources. Although ROSAT has discovered more than 75,000 sources in its all sky survey (and comparable numbers in the pointed observations), these source are unlikely to account for the major constituents of the CXB. Evidence is increasing that the CXB is dominated by heavily obscured sources which show up only at energies above the ROSAT band, and which are poorly sampled by the existing all sky surveys completed with collimated proportional counters. While many sources in a 2-10 keV survey will appear in the ROSAT catalog, many others will be new. ABRIXAS will discover 15,000 hard band sources with fluxes above $\sim 10^{-12}$ erg s $^{-1}$ cm $^{-2}$, about one tenth the number expected from the survey proposed in the following section. The 2-10 keV catalog will have near uniform sensitivity across the whole sky, as the effects of absorption are relatively small.

3. The Present Epoch Plus Concept

We propose a concept capable of performing an all sky surface brightness survey and making the deepest yet X-ray catalog in the 2-10 keV band. As the primary energy range of interest is > 2 keV, both of these surveys will be relatively unaffected by galactic absorption. Additionally, the survey will detect more than 5 times as many sources in the 0.5-2 keV band and make precise surface brightness measurements there as well. All of this is accomplished by putting a large number of ASCA style telescopes into a MIDEX sized payload and scanning the sky for 2-3 years. Geometric considerations show that at least 28 ASCA sized telescopes (diameter 38 cm) can be placed within the 274 cm shroud of a Delta launch vehicle. Although the detailed engineering has not yet been

done, it is clear that we can use the effective area that would be achieved by 28 ASCA telescopes is a plausible estimate. The focal plane instrumentation would not require 28 separate detectors, but could use, for instance, the innovative design of the ABRIXAS system in which one large 6 by 6 cm CCD is shared among seven telescopes.

We have performed ray tracing simulations using realistic representations of the ASCA mirrors (K. Gendreau, private communication), representative detector efficiencies for CCDs, and an exposure which corresponds to a 2 year mission which achieves 70% efficiency (comparable to the achieved ROSAT efficiency; we might do better than ROSAT in a lower inclination orbit). This is equivalent to performing a series of 817 second exposures with a single ASCA GIS system on a grid of points separated by $10'$ in each direction. The input photons were generated from a randomly distributed collection of sources which obeyed a Euclidean log N-log S law, each of which had a 1.7 photon index spectrum. The normalization of the log N-log S power law was 150 sources per square degree at $10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$, with the faintest source being determined by the condition that the total 2-10 keV flux match the observed value ($5 \times 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$). The faint sources supply the bulk of the CXB against which the brighter sources must be detected. ASCA SIS performance suggests that the CXB will produce 5 times as many photons as the instrument background. This simple simulation should be adequate to assess 2-10 keV sensitivity. These are conservative simulations given that the point spread function of foil mirrors now being produced in our laboratory for ASTRO-E are substantially better than achieved for ASCA; improvements will not increase the collecting area, but will allow smaller detection cells (with lower background rates per cell) to be used. The simulations accepted all photons which start within 2° of the pointing direction and arrive within 2° of the center of the field of view at the focal plane. About 30% of all detected photons are assigned a position in the resulting image $> 30'$ from their celestial point of origin, so PEP will require a 1° collimator in front of the mirrors (or a clever baffling system) to eliminate these photons (most of which are single reflections or reflections off the back of some of the foil segments). The simulation produced $\sim 14,000$ photons per square degree without including the collimators; we therefore anticipate that the 2 year mission just meets the 1% goal once the effects of collimators are included. A sliding box cell algorithm (with $7 \times 7'$ detect cell and 6σ significance criteria) detected 48 sources within a 44 square degree region and is complete to just under $3 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$; improvements already demonstrated in mirror point spread function will lower the flux threshold below $2 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ in accordance with an independant analytic estimate (R. Warwick, private communication).

4. Is a Medium Explorer Necessary?

A similar experiment concept using only proportional counters and capable of achieving a statistical sensitivity of 1% per square degree has been presented by Barcons and collaborators (Barcons et al. 1997, Barcons 1997). Although a relatively large collecting area is required, this experiment can plausibly fit within the constraints of the NASA SMall EXplorer (SMEX) program. Barcons et al. (1997) make the case for why 1% per square degree is a desirable sensitivity. Briefly, measuring the power spectrum requires constructing the P(D) curve (the distribution of observed surface brightnesses) and comparing the measured distribution to a predicted one. The prediction can (in the post AXAF era) include precise information about the log N-log S distribution as well as details about exposure and statistical sensitivity. Deviations from the prediction carry information about effects not included, such as clustering of sources. Sensitive measurements of the clustering (from which the power spectrum can be derived) are limited by the the total number of independent measurements (which argues for a small beam) and the statistical precision of each measurement (which argues for a large beam if exposure and area are fixed). The 1% per square degree figure of merit provides a statistical sensitivity substantially smaller than the expected fluctuations (of order 10% for 1 square degree beams) with a large number of independent measurements. Our concept requires a larger collecting area simply because focussing optics are much less efficient than collimated proportional counters. Particularly above ~ 2 keV, where atomic edges leave a noticeable drop in the efficiency of all astronomical X-ray mirrors, the net efficiency is $< 25\%$ compared to the proportional counter, requiring large raw collecting area. It is necessary to then ask, what benefits are derived from the larger (and more costly) concept presented here. The advantages are:

- (a) This concept produces a contemporaneous X-ray catalog with an estimated 150,000 extragalactic sources of flux $> 2 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 2 -10 keV band and more than 600,000 sources independently identified in the band below 2 keV.
- (b) The contemporaneous survey allows direct removal of the brighter sources from the P(D) curve, increasing sensitivity to the power spectrum at intermediate redshift. The proportional counter experiment must mask pixels identified from a non contemporaneous survey, thus losing signal and introducing the additional uncertainty of whether the sources at the catalog limit were in fact bright when the surface brightness measurements were made. Barcons et al. (1997) quantify this uncertainty in terms of typical variability of sources with mean flux of $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ but this variability is in fact not well known.

(c) The imaging survey allows the brighter sources to be removed without masking an entire 1 square degree sky pixel. Not only does this allow the removal of fainter sources, but the sources can be removed without masking entire pixels which would substantially reduce sensitivity.

(d) The catalog allows an independent measurement of the power spectrum in the present epoch.

(e) The focussing concept will have much much better sensitivity for searches limited by shot noise, such as a spherical harmonic decomposition (Lahav et al 1997) or a cross correlation with the CMB (Boughn et al. 1997).

5. Comparison with other missions

The best all sky surface brightness survey in the 2-10 keV band is still the HEAO-1 A2 survey (Shafer 1983, Boldt 1987, Allen et al. 1994). The A2 experiment achieved fluctuation dominated sensitivity, but only on scales of ≥ 5 square degrees; the only uniform and contemporaneous source catalog is derived from the same collimated proportional counter experiment and reaches only $3 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Piccinotti et al. 1982). Although this survey continues to be of interest for cross correlation with various other surveys (e.g. the CMB (Boughn et al. 1997) and the soft X-ray background (Miyaji et al. 1996)) the limited angular resolution now limits the sensitivity. The Piccinotti et al. (1982) survey will soon be replaced as the deepest complete X-ray survey in the band above 2 keV by the ABRIXAS mission (Trumper 1997). PEP will detect an order of magnitude more sources than ABRIXAS, but more importantly, has significant sensitivity to surface brightness. ABRIXAS will detect 0.11 and 0.34 count/sec over the field of view from the CXB and the instrument background, respectively, in the 2-10 keV band (P. Friedrich, private communication). In a 3 year mission with 70% efficiency, ABRIXAS will achieve a precision of only 15% per square degree. The increase in signal to noise for PEP compared with ABRIXAS is largely due to the increased efficiency achievable with the longer (4 m vs 2 m) optical bench. While the possibilities opened by ABRIXAS source catalog will take many years to exploit, that experiment will not contribute to any of the experiments requiring surface brightness measurements. The combination of deep catalogs and surface brightness measurements give PEP unique capabilities.

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